

# On-line assessment of brightness and surface kinetics during coffee roasting

J.A. Hernández<sup>a,\*</sup>, B. Heyd<sup>b</sup>, G. Trystram<sup>b</sup>

<sup>a</sup> *Research Center of Engineering and Applied Sciences (CIICAp), Autonomous University of Morelos State (UAEM),  
Av. Universidad No. 1001 Col. Chamilpa, C.P. 62209, Cuernavaca, Morelos, Mexico*

<sup>b</sup> *Joint Research Unit Food Process Engineering (Cemagref, ENSIA, INAPG, INRA) ENSIA, 1 avenue des Olympiades, 91744 Massy Cedex, France*

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## Abstract

Image analysis enables the on-line measurement of essential values such as bean color and surface area. However, it is difficult to apply this technique to coffee roasting. In this industry, color (i.e. brightness) is a key variable which determines the quality of the final product, but it is evaluated experimentally in the laboratory by the roast master. In order to control the process, it is necessary to develop a technique which enables a real-time assessment of product quality. This work proposes a method to determine brightness and surface area using image analysis, on-line during coffee roasting. The changes to brightness and surface area that affect coffee bean during the process were studied experimentally in a roaster equipped with a CCD video camera, a lighting system and two small fiber optic spot-lights. *Arabica* green coffee beans of Colombian origin were roasted using different air temperatures (190, 200, 210, ... 300 °C) for 10 min. The experimental results provided knowledge of the process, and also, allowed us to observe the behavior of color and surface kinetics. It was also possible to perform experiments real-time using image analysis system, stopping the roasting process when the results were optimum. When the bean temperature reached 280 °C, the surface area stopped increasing, so that roasting was also complete. Brightness and surface area may be two indicators to ensure on-line quality during coffee roasting.

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## 1. Introduction

Coffee roasting is a very important unitary operation to develop the specific organoleptic properties (flavors, aromas and color) which underlie the quality of coffee and guarantee a good beverage. Nevertheless, this process is highly complex, since the quantity of heat transferred to the bean is crucial. During coffee roasting, moisture loss and chemical reactions (oxidation, reduction, hydrolysis, polymerization, decarboxylation and many other chemical changes), as well as major changes (to color, volume (swell), mass, form, bean pop, pH, density and volatile

components) occur, and CO<sub>2</sub> is generated. Finally, after these considerable changes, the beans must be cooled rapidly to halt the reactions (using water or air as a cooling agent) and prevent excessive roast which will alter product quality (Schwartzberg, 2000; Illy and Viani, 1998; Nagaraju et al., 1997; Raemy and Lambelet, 1982; Raemy, 1981; Singh et al., 1997; Sivetz and Desrosier, 1979).

The quality of roasted coffee is evaluated experimentally in the laboratory using different parameters (for example: aroma, flavors, color, bean temperature, pH, chemical composition, bean pop, mass loss, gas composition and volume) (Hernández Pérez, 2002; Schwartzberg, 2000; Illy and Viani, 1998; Nagaraju et al., 1997). However, in the industry, it is very difficult to estimate these parameters on-line, and in most cases the roast master has an essential role to play. He determines the operating conditions based

\* Corresponding author. Tel.: +52 (777)3 29 70 84; fax: +52 (777)3 29 79 84.

E-mail address: [alfredo@uaem.mx](mailto:alfredo@uaem.mx) (J.A. Hernández).

on measurements experimentally in the laboratory concerning organoleptic properties (color, aroma and flavors), and physical parameters (air temperature and stay time of the process) (Hernández et al., 2007). The process is then adjusted for the next batch. This method is only effective if the quality of the raw material does not vary between laboratory measurements, which is not the case in the food industry. Thus in order to control the process, it must be possible to perform on-line measurements of product quality.

The principal objective of image analysis is to assist human perceptions of the visual phenomena (progress of images or their reconstruction) arising from the optical creation of measurement systems using color and magnitude, and also to provide controls for the environment of robotic systems (Kar and Dash, 1999). In most cases, evaluations of product quality in the food industry involve sensory, microbiological and nutritional aspects. Sensory aspects such as color and aroma are important to the initial appreciation of roasted coffee, because taste and texture are not easily evaluated on-line by a roast master. Color is therefore, a parameter which must be controlled. Today, image analysis sensors and algorithms enable an analysis of the properties of both the final product and in-process materials, using essential values such as color and, surface and visual texture (Kar and Dash, 1999; Hernández Pérez, 2002; Guizard et al., 1992).

We therefore identified the need to develop a reliable experimental system. The aim of this work was thus to develop an experimental system capable of evaluating the on-line color and surface of beans during coffee roasting and thus enable, control of the roasting process.

## 2. Material and methods

### 2.1. Green coffee and roasting conditions

Eight Colombia green coffee beans (*Arabica*) were roasted using a hot air flow as the heating medium. The experiments were carried out at a constant air velocity of 4 m/s which generated constant air temperatures (190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290 and 300 °C) for a period of 10 min. All experiments were performed in triplicate.

### 2.2. Coffee roaster

A static roaster (SERVATHIN Series SV02 7817) was used to perform roasting experiments. A diagram of the roaster is shown in Fig. 1. The coffee beans were placed on a mesh grid to maintain them in a static suspension, as convection was the predominant mode of heat transfer. During coffee roasting, the air temperature, bean temperature and bean mass were measured as reported by Hernández et al. (2007). Color pictures of the beans were also acquired on-line.

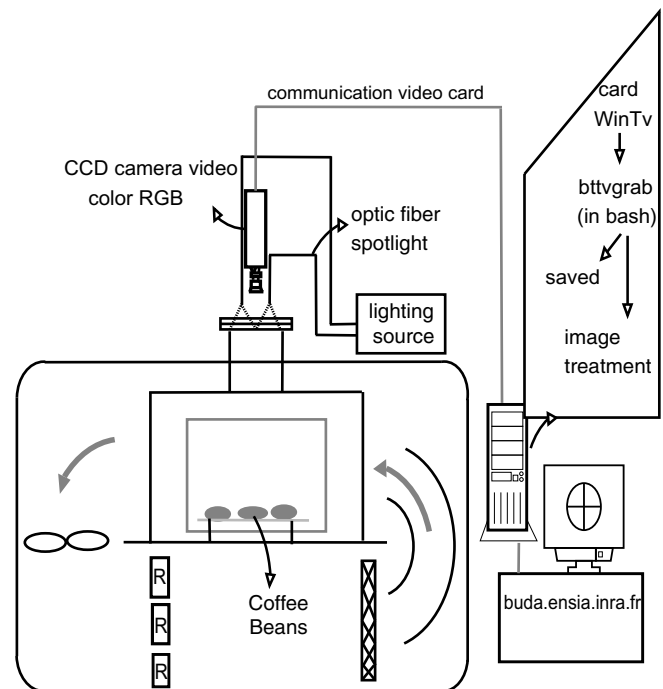


Fig. 1. Diagram of experimental apparatus used (color and surface).

### 2.3. Data acquisition system

Fig. 1 shows the experimental system which was developed to monitor the on-line color [red, green and blue] (or brightness measured by the grey level) and the surface (projected area) of the coffee beans during roasting. This experimental system comprised a standard device for image analysis:

- An illumination system: a light source with two small fiber optic spotlights,
- An image sensor: a CCD video camera (charge-coupled device) RGB color (red, green and blue) from SONY (XC-711P) operated with 50 mm  $\phi$ 25.5 objective,
- A digitization system: a computer was used, equipped with a *Hauptpage WinTV* video acquisition card and a *bttv 878* converter for image digitization. We deliberately used these commercial systems because of their robustness and lower cost, and particularly the availability of source codes for the software pilots for the *bttv 878* component enabling modification for specific use.
- A temperature acquisition system:
  - Thermocouples (type K) to measure the air temperature to a precision of  $\pm 0.5$  °C,
  - an Arcom SCB7 thermocouple conditioner connected to the personal computer and,
  - an Arcom PCAD12/16H A/D converter for acquisition of the air temperature in the roaster.

Data acquisition and I/O port programming were written in C (Lawyer, 2000; Photis, 1999). On-line data processing was performed using a program written in

Octave (Eaton, 2001) and an algorithm managed under *bash* (Bourne, 2002).

#### 2.4. Image processing system

As shown in Fig. 1, the video camera was installed outside the roasting cell and visualized events through a glass window (the image distortion induced was negligible). *bttgrab* software was used for image acquisition (Walter, 2001). This software has the advantage that it can be used with a program written in *bash*, enabling simple on-line image processing and process control. Color images were stored on the hard disk in a ppm (portable pixel map) format at regular intervals (one image every 20 s) with a definition of 480 · 640 pixels. The image analysis system comprised three stages: acquisition (visualization of objects, numeration), processing and then extraction of the information. It is important to note that all measurements (air temperature, color and surface) were acquired on-line, so that process decisions could be taken real-time.

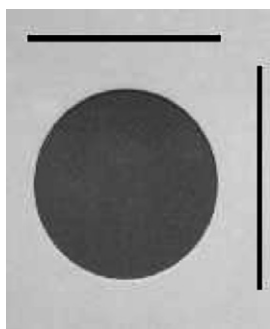


Fig. 2. Diameter of the circle used to calibrate distance – 3 cm.

#### 2.5. Processing and extraction of image information

The aim of image processing and extraction was to enable on-line control of the roasting process based quality parameters (color and surface), and to determine the degree of coffee roasting. In order to simulate industrial conditions as closely as possible, we chose not to control the light level. The images acquired thus depended on the experimental conditions, resulting in heterogeneous images (each point of the image not receiving either the same quantity or quality of light). Before, each experiment, the system was calibrated, using a color palette which was photographed under exactly the same conditions as the beans (Hernández Pérez, 2002). The video camera always had fixed aperture and focus. Bean quality was determined in terms of brightness, which is measured using the grey level of bean pixels Eq. (1) after a threshold value had been fixed:

$$\text{Grey level} = \frac{\text{Red} + \text{Green} + \text{Blue}}{3} \quad (1)$$

Finally, a mean grey value for the beans was calculated and the pixel size was also determined.

#### 2.6. Pixel size determination

Distances on pictures were counted in numbers of pixels. These depended on the experimental conditions and particularly on the focal length of the objective and the distance of objects from the camera. It was therefore necessary to perform a calibration in order to convert the distance expressed as a number of pixels, into millimeters. To achieve this calibration, we took a picture representing a circle with a diameter of 30 mm on a white background (Fig. 2). The *length* and *height* of the circle could be determined simply by choosing lines or columns of the matrix, as shown in Fig. 3. It was possible to determine the surface

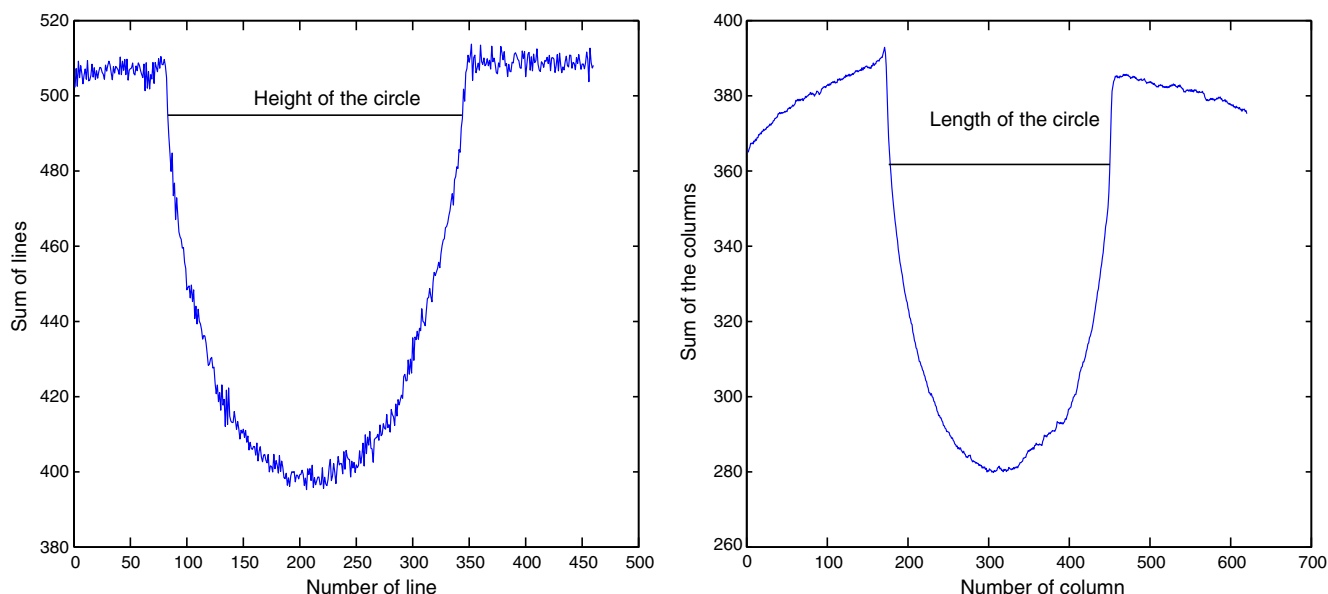


Fig. 3. Analysis of the circle used to calibrate the distance.

of the limited square in the circle in a number of pixels, in order to calibrate the surface area of this square. The pixel surface area was  $0.0125 \text{ mm}^2$ , and, because of the long optical focus, this result was similar whatever the position of the circle on the picture.

### 3. Results and discussion

#### 3.1. Experimental kinetics of on-line air temperature

Fig. 4 shows the experimental course of air temperatures versus time. Air temperature was measured on-line 2 cm upstream of the beans, for a temperature regulated at  $220^\circ\text{C}$ . The average air temperature measured was  $223^\circ\text{C}$ , i.e.,  $3^\circ\text{C}$  higher than that shown by the roaster. This could be explained by the position of the regulating thermocouple which was situated 40 cm away from the coffee beans. For this reason, all our calculations took account of the measured air temperature. Fig. 4 also shows that the temperature

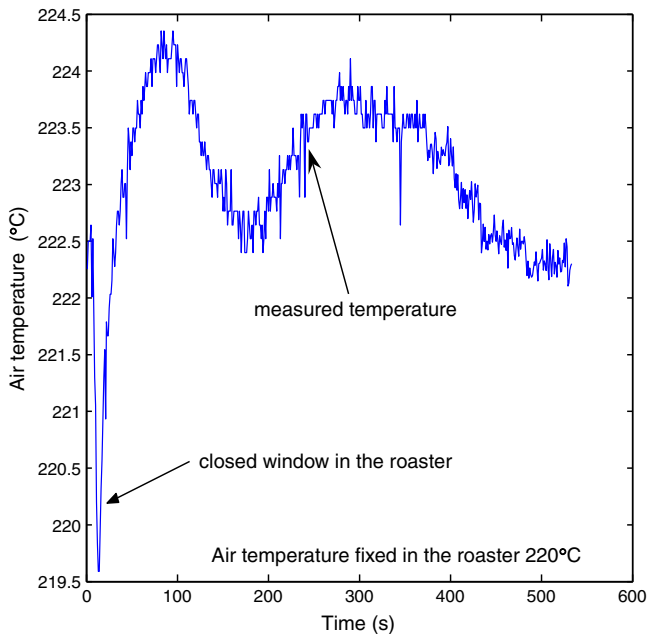


Fig. 4. Air temperature measured on-line versus time to  $220^\circ\text{C}$ .

was not wholly stabilized after 600 s, but the amplitude remained smaller than  $2.5^\circ\text{C}$ , which we felt was acceptable.

#### 3.2. Color and grey kinetics of experimental data

Fig. 5 shows the color values ([red, green, and blue] system) measured using the CCD video camera and corrected during coffee roasting for a roasting air temperature fixed at  $240^\circ\text{C}$ . The behavior of curves was similar, with a rapid reduction after 20 s, followed by an almost symmetrical growth (around 60–100 s), and then an uninterrupted exponential decline.

Fig. 6 represents the evolution of the mean brightness of beans during roasting at different air temperatures. Under high air temperatures ( $\geq 260^\circ\text{C}$ ) changes to the grey levels were more rapid during the process. The grey curves thus show that air temperature and time are two crucial factors during the process of roasting. A repetition of the assays, plotted on the brightness curves, revealed satisfactory reproducibility.

In order to better understand the behavior of these curves (Fig. 5 and images of beans), they were studied in terms of bean temperature as a function of time (Fig. 7). Four different stages could be observed during the process:

- (1) the color of beans remained the same during an initial period (from 0 to 20 s),
- (2) when the internal temperature of beans reached  $100^\circ\text{C}$  (Fig. 7), their color darkened slightly (approximately 20–60 s), which could be attributed to the vaporization of unbound water,
- (3) above  $160^\circ\text{C}$ , the beans were markedly lighter in color (period between 60 and 100 s),
- (4) their color then darkened gradually to reach that of burned coffee (determined visually).

#### 3.3. Determination of on-line quality from coffee roasting grade

At each time point, on-line image analysis enabled a comparison between the measured grey level and a target grey

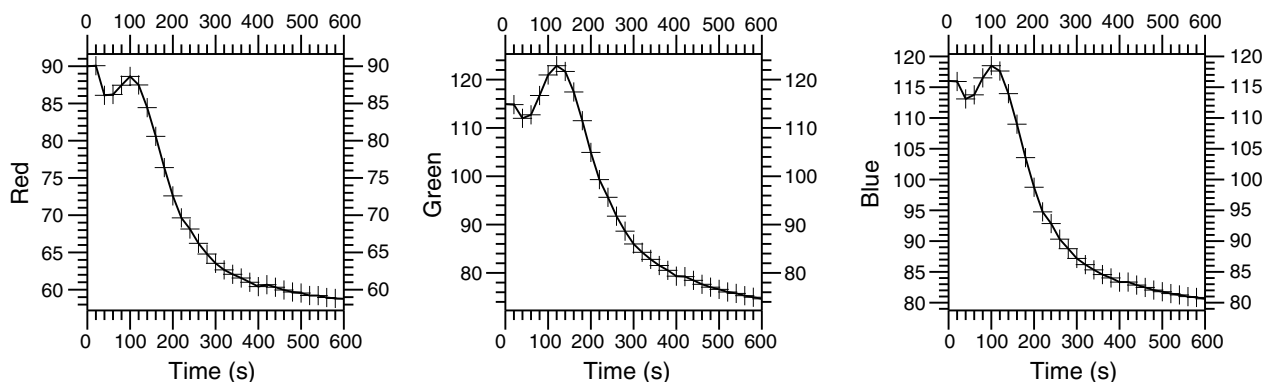


Fig. 5. Color kinetic in red, green and blue versus time for an air temperature fixed by the roaster at  $240^\circ\text{C}$ .

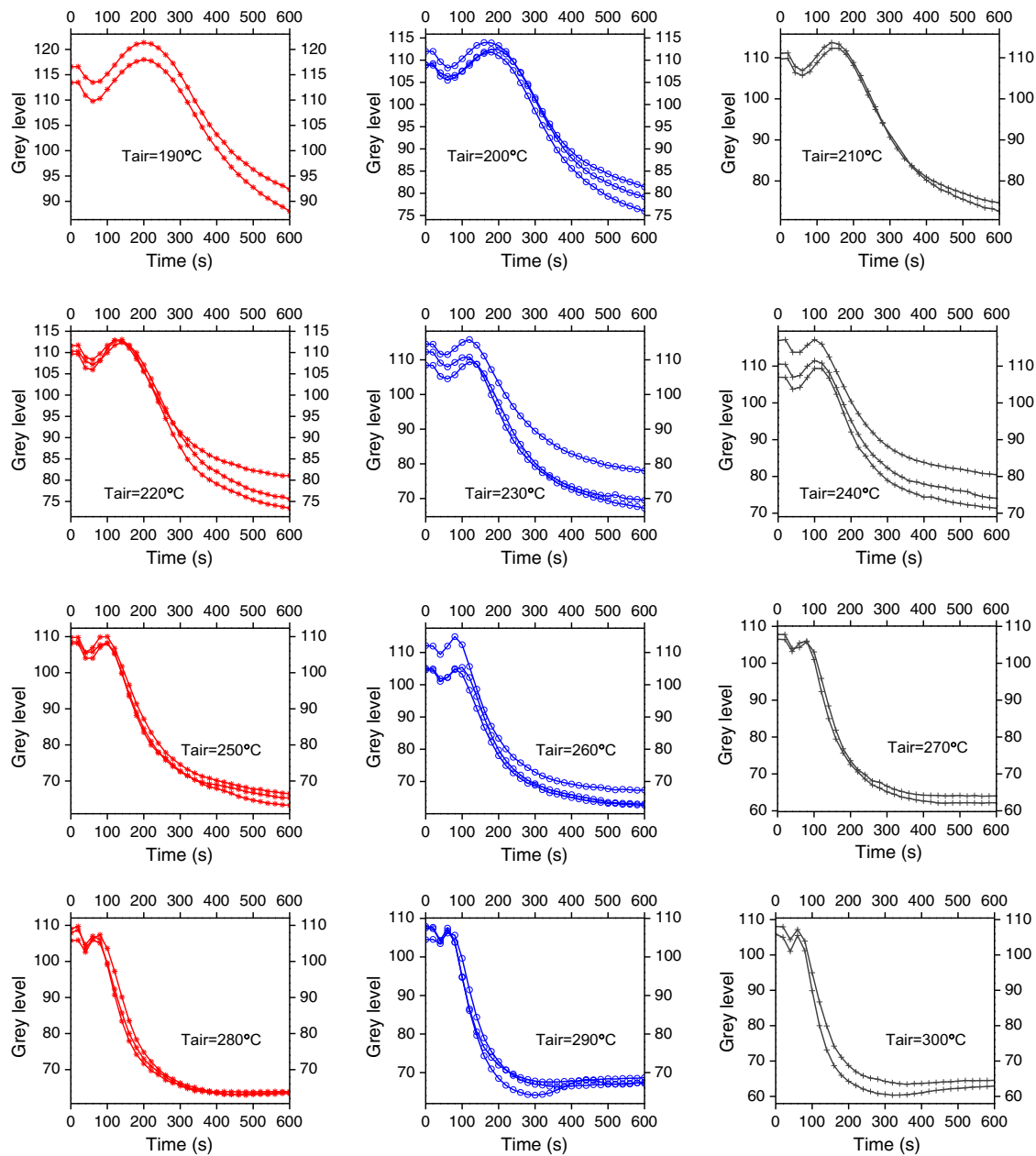


Fig. 6. Grey level kinetics for all experiments and their repetitions.

level determined under the same conditions the latter being the value corresponding to optimally roasted coffee beans. During this experiment, the target was *Arabica* coffee roasted by a roast master with a measured mean grey value of 70.5.

Fig. 8 shows the on-line values obtained for brightness versus time of roasting during an experiment conducted at 230 °C. The process was stopped when the grey level of the coffee beans reached the optimum value determined by the company. In addition, this Fig. 8 presents three images (target roasted coffee, green coffee and roasted coffee after the process). The roasted coffee obtained after this experiment appeared to be very similar to the target coffee, and the drink obtained was deemed acceptable by the laboratory team.

This test confirms that it was possible to adjust the roasting process on-line in order to optimize product quality.

In addition, Fig. 9 shows some raw images (unprocessed) of a coffee bean during roasting at an air temperature of 230 °C. This figure also includes the experimental curve of grey level versus time for all roasting experiments. Image ( $gA_{(t=0)}$ ) corresponds to unroasted coffee. From Fig. 9, it can be seen that the grey level fell between 20 and 60 s of roasting ( $gB_{(t=40)}$  and  $gC_{(t=60)}$ ). Images  $gD_{(t=100)}$ ,  $gE_{(t=120)}$  and  $gF_{(t=140)}$  show the increase in bean brightness, reflected by a pale yellow color. Images  $gG_{(t=160)}$  and  $gH_{(t=180)}$  demonstrate the change from pale yellow to reddish-brown. This change of color reddish-brown was also

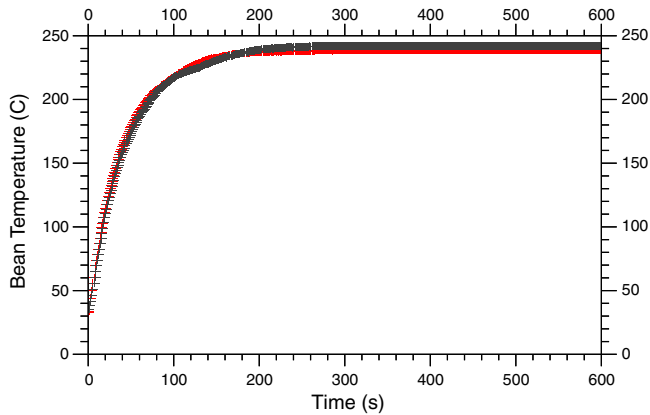


Fig. 7. Bean Temperature versus time for an air temperature fixed at 240 °C.

observed by Illy and Viani (1998). Image  $gI_{(t=220)}$  showed the change from reddish-brown to a dark color and finally, images  $gJ_{(t=320)}$  and  $gK_{(t=520)}$  showed an even darker color.  $gL_{(t=640)}$  was the optimum color of beans (see Fig. 8).

### 3.4. Experimental data on bean surface kinetics

After calibration of the pixel surface, the bean surface area was measured in  $\text{mm}^2$  from the number of pixels counted on the image. Fig. 10 shows the increase in bean surface area as a function of the air temperatures and roasting times studied. These surface curves (Fig. 10a) show an increase of between 15% and 70%, corresponding to air temperatures between 190 °C and 300 °C. Moreover, Schwartzberg (2000) demonstrated a 50% at 120% expansion in bean volume at air temperatures between 270 °C at 550 °C with the different roasting system used. Dutra et al. (2001) determined a 120% increase in volume after roasting for 12 min at an air temperature of 275 °C, using a direct heating method (which is no longer employed in industry). Air temperature is thus one of the key parameters affecting the increase in coffee bean surface area during roasting. It should also be noted that at air temperatures of between 280 °C at 300 °C and after the longest period (360 s), the increase in surface area almost ceased (see Fig. 10a), the optimum bean temperature was exceeded and consequently the roasting phase was completed. Coste

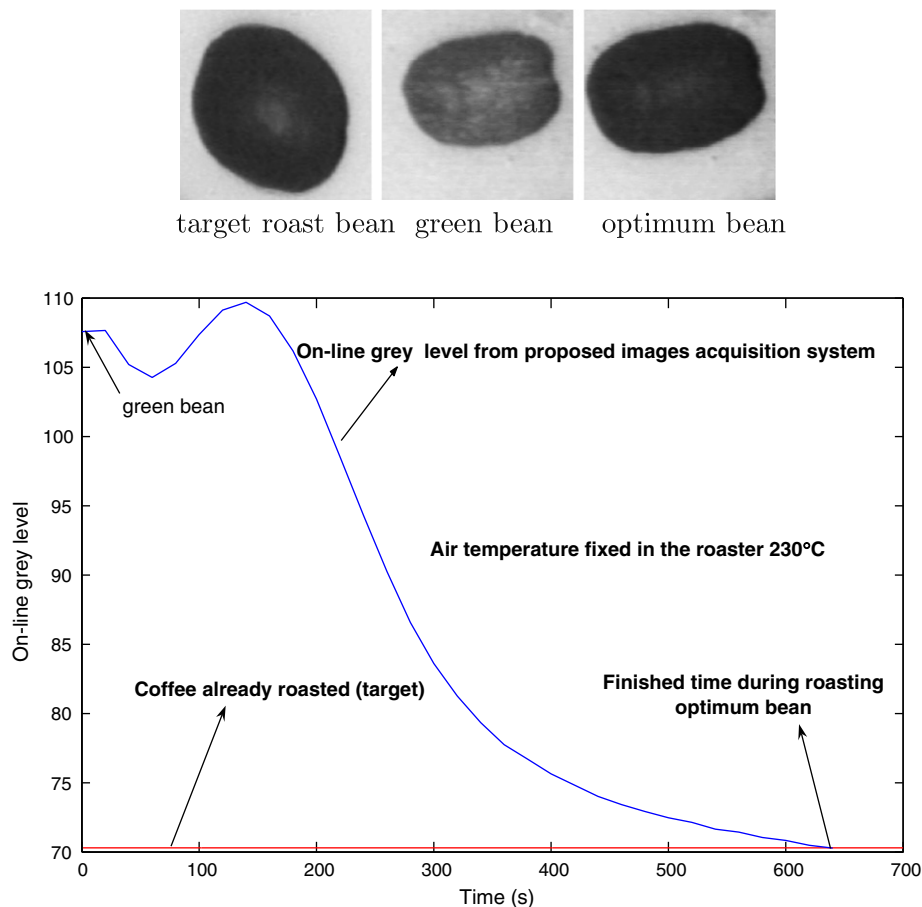


Fig. 8. On-line grey level kinetics from image analysis, and optimum grade of coffee roasting.

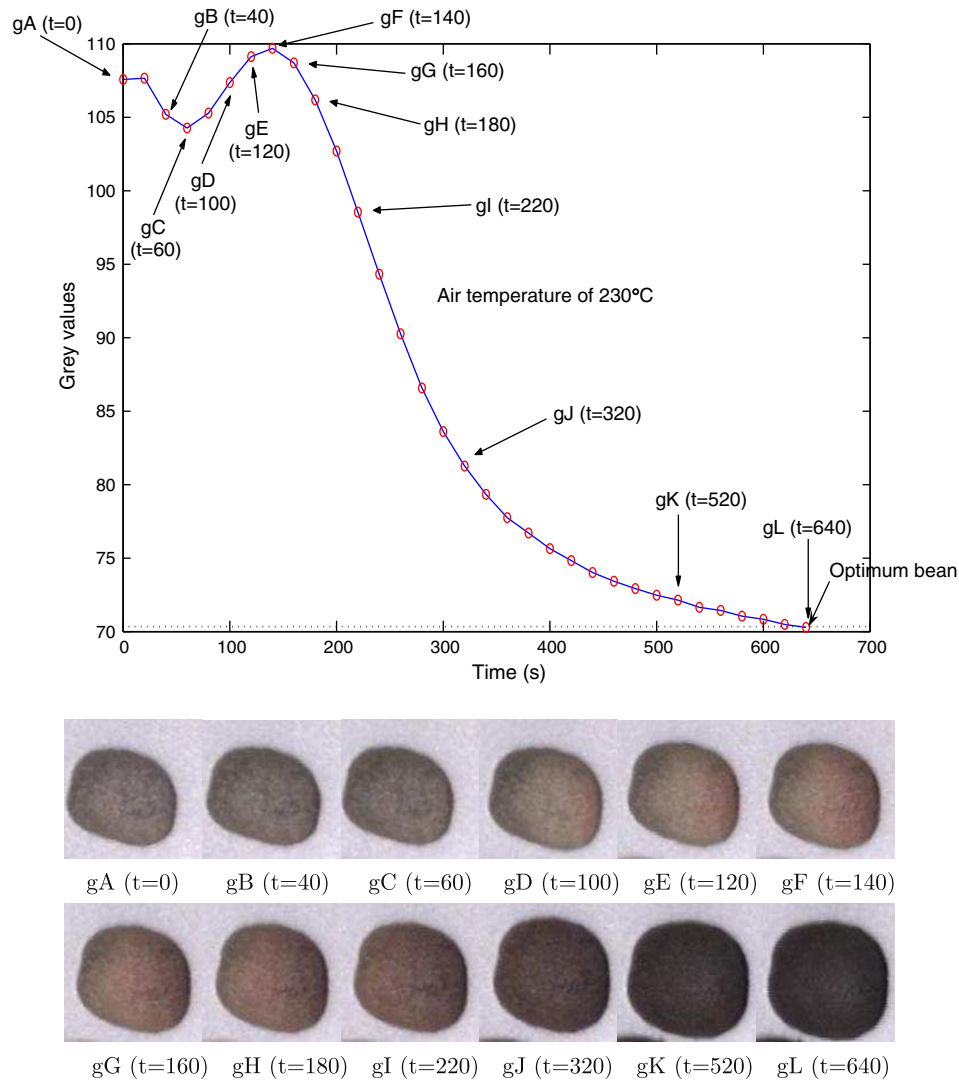


Fig. 9. Image of coffee bean during the roasting process, with an air temperature fixed by the roaster at 230 °C.

(1968) specified that the volume of the coffee beans no longer increased above a temperature of 280 °C.

To better understand this phenomenon, Figs. 10a and b also show the surface kinetics and temperatures of beans as a function of time for an air temperature of 190 °C. Fig. 10b provides evidence that coffee beans only begin to swell when their internal temperature reaches more than 100 °C, thus confirming the hypothesis put forward by Guyot (1993) which attributes this expansion to the pressure of water steam. On the other hand, Dutra et al. (2001) mentioned that the increase in the surface area was caused by three phenomena occurring during the roasting process: water vaporization, the release of carbon dioxide CO<sub>2</sub>, and the release of volatile components from beans.

It is important to highlight our observation that bean expansion was the same in all directions. To achieve this, we analyzed the swelling of coffee beans from three different angles during roasting (above, vertical and below, see Fig. 11). We observed that the three views of beans thus

analyzed involve homogeneous swelling (Hernandez et al., 2000). As a result, it was easy to calculate the volume from the projected surface area.

#### 4. Conclusion

This work shows that it is possible to acquire and process on-line images during coffee roasting in order to measure product quality real-time (in this case, brightness). This success is a result of parallel task scheduling. In fact, the time required to process each image is about 4.4 s, and an image is acquired every 20 s. This 20 s period is sufficient for the on-line determination of quality. It enables on-line adjustment of the process (roasting time) in order to maximize product quality (similar brightness to target beans).

We generated a large database of repeated experimental information, including bean temperature, mass, color [R, G, B] and surface area as a function of time. It is difficult to acquire such a large database of major variables under industrial conditions. It is therefore important to

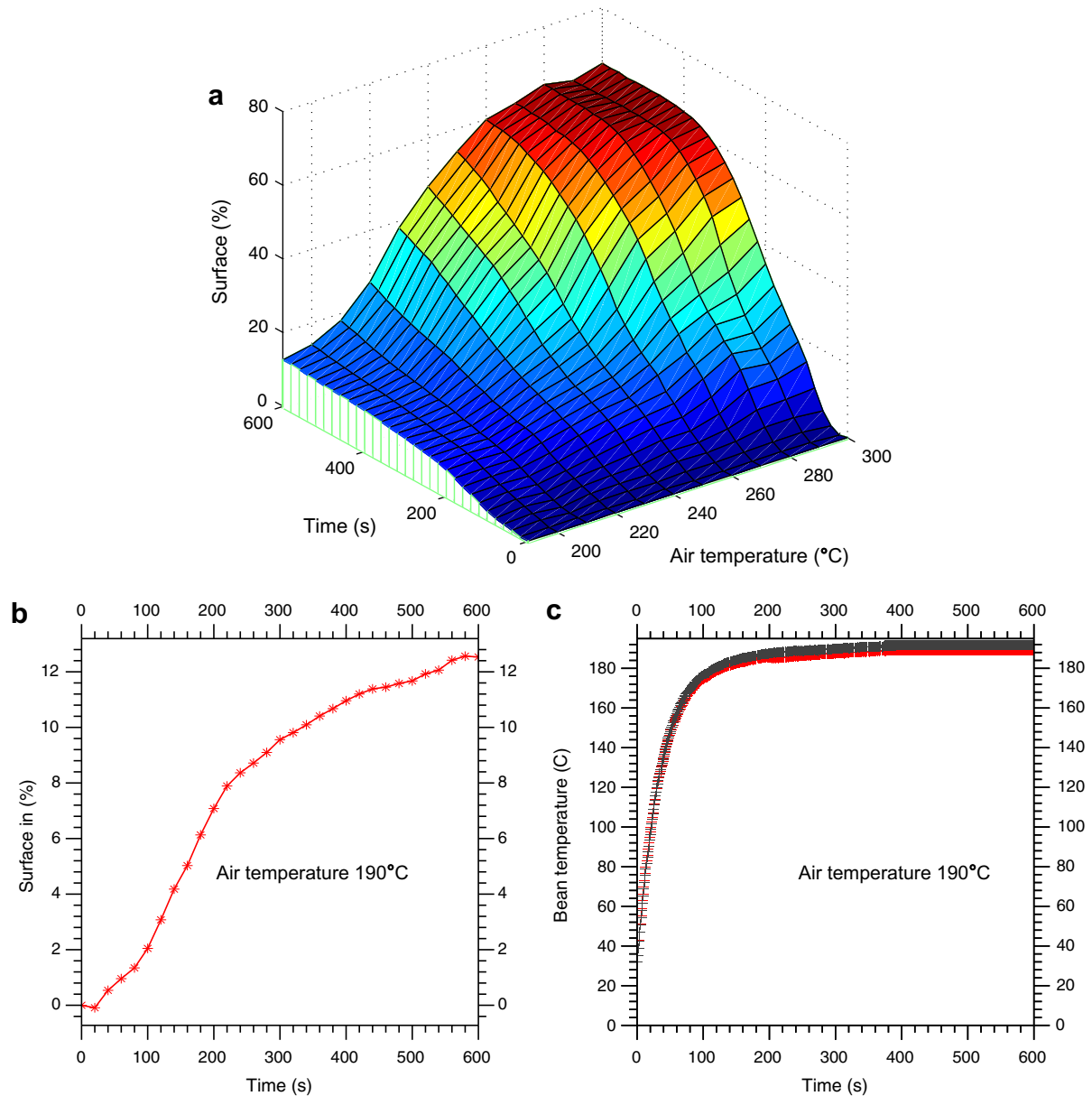


Fig. 10. Experimental kinetics of the increase in bean surface area and temperature. (a) curves of bean surface area as a function of time and air temperatures; (b) one experiment concerning surface area versus time; (c) the same experiment, but using bean temperature versus time.



Fig. 11. Expansion of the bean is homogeneous, from below (a), vertically (b) and above (c).

clarify possible links between different correlated quality variables in order to restrict industrial instrumentation to robust sensors supplemented by algorithms which will

enable of on-line determination of product quality and control of the process.

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